International Conference on Space Optics—ICSO 2022

Dubrovnik, Croatia

3–7 October 2022

Edited by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny,

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International Conference on Space Optics — ICSO 2022, edited by Kyriaki Minoglou, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 12777, 127770H · © 2023 ESA and CNES · 0277-786X · doi: 10.1117/12.2688820

Optical communication requirements for scientific missions and the Deep Space Gateway

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ABSTRACT

The growing interest into exploration of the Moon poses several technological challenges, one of them is surely the need to ensure that the future Moon robots and inhabited colonies will be able to rely on a solid and performing communication infrastructure both within the Lunar environment and with Earth control centers.

In this view, a study with ESA (OCRSG) has been carried out by TASI, SSSA and TASCH, in order to start the design of such infrastructure. Several optical terminals have been sized to guarantee a downlink from the Moon to Earth at >2 Gbps, and the same performance between Moon orbiters and Moon surface users, and among orbiters themselves, including the future Lunar Gateway.

The design is based on state-of-the-art technologies; we also compared the existing radio-frequency subsystem performance, demonstrating the advantages of optical technologies.

The optimal modulation scheme for each scenario has been individuated, starting from high-photon-efficiency modulation (HPE/PPM) but preferring, when possible, more "conventional" schemes, like OOK and DPSK (to exploit a better technological availability). This optimization was possible thanks to the consideration of high power optical boosters which are now available for terrestrial applications.

Another part of the study focused on the definition of FoR (Field of Regard) requirements for the different use cases: this realization can be done in different ways, e.g. using a single mirror mechanism up to a fully hemispherical gimballed or periscopic telescope.

The study conclusion also draws a technological roadmap, addressing the critical technologies in the gap between the state-of-the-art and the baseline design.

Keywords: Moon, optical communications, optical terminal, modulation, booster, FoR, roadmap.

1. INTRODUCTION

The second era of Lunar exploration is starting now. Its goal is to expand humanity into the Solar System, thereby developing new markets, and new economic opportunities. In this view, the Moon will be seen as a place to practice exploration, but now also to learn how to harvest resources, develop industries, and build communities. The European Space Agency is working towards the preparation of a new program under the name "Moonlight Initiative" with the vision to enable the implementation of an European-led delivery of Lunar Communications and Navigation Services (LCNS) that will support the next generation of institutional and commercial Lunar explorers, as well as possibly enhancing those mission currently under definition. Furthermore, the emergence of the Lunar Gateway and the involvement of Europe as a contributing partner also pushes the need to establish a reliable and performing communications infrastructure with the Moon-orbit environment.

The Interagency Operations Advisory Group (IAOG), where ESA participates as a member, has conducted over the past years an internal study ([1]) to define a possible overall Lunar Communications Architecture, and to identify the different communication links between the different nodes and the related frequency assignations. In this view, optical communications are introduced for several scenarios, because they can offer a great advantage in terms of efficiency and support for high data rates, exploiting high photon efficiency modulations as defined by the CCSDS standards [3] and [4].

The feasibility of optical communications between the Moon and the Earth was demonstrated in 2013 with the Lunar Laser Communications Demonstration (LLCD) payload on board the Lunar Atmosphere Dust Environment Explorer (LADEE). The LLCD terminals implemented a bidirectional communications link with 20 Mbit/s uplink and 622 Mbit/s downlink data rates.

The study "Optical communication requirements for scientific missions and the Deep Space Gateway" (OCRSG), the outcomes of which are reported in this paper, focused on high rate (2.1 Gbps) Lunar optical communications, in relation to the ARTES 4.0 SPL Optical communication – ScyLight work plan.

The objectives of OCRSG were:
1) To investigate / review the end-to-end communications architecture for long distance communications or scientific missions, focusing those in the cis-lunar region as well as the Deep Space Gateway, and to assess the associated communication link requirements.
2) To perform a preliminary design of the optical terminals required to support communications, either based on the HPE standard (modified to implement high data rate bi-directional communication), or on other schemes, if demonstrated to be more adapt to such links, and on established requirements at the overall optical terminal level.
3) To identify the critical subunits of the optical terminals and to define the associated performance requirements.
4) To perform a technology survey and derive the technology roadmap for the critical technologies (e.g., optical/optoelectronic).

2. SYSTEM SCENARIO

The study started from a complete overview of all the different communications' scenarios involved in the future Moon exploration missions, as well as of the existing heritage on RF and optical links in such environment, and of the related regulations and standardizations which IOAG aims to harmonize, with the aim to define the system into which the optical communication terminals will be integrated and to derive the related preliminary requirements.

2.1 Future lunar settlements

The incoming new Moon exploration era will be driven by both Agencies and private sector.
In particular, the following organizations are currently taking care of the Moon exploration future plans:

- Moon Base Alliance: https://moonbasealliance.com/ https://moonbasesummit.com/
- Lunar Explorers: http://www.lunarexplorers.net/
- Space Adventures: https://spaceadventures.com/ planning space station visit, then moon trips
- Space Renaissance International: https://spacerenaissance.space/
- Interagency Operations Advisory Group (IOAG) founded by the Interoperability Plenary (IOP) which provides a forum for identifying common needs across multiple agencies related to mission operations, space communications, and navigation interoperability. A specific IOAG goal is the achievement of full interoperability among member space agencies. Their work has addressed the LCAWG (Lunar Communications Architecture Working Group) to produce the document "[1]-Lunar communications architecture study report" which is the basis of this study.

The future Lunar settlement, according to [1], is composed by the Lunar Orbiting Platform-Gateway (LOP-G), plus an unprecedented number of lunar missions foreseen for the next decade. This includes institutional missions, but also commercial ones – this being a new trend: in total more than 40 missions, approximately 80 space vehicles planned by or involving 10 space agencies, plus several endeavors by private sectors, e.g., Moon Express, Astrobotic, and Blue Origin).

Such missions will foresee:

- International Lunar Orbiting Platform-Gateway (which will perform Science, Exploration and include a Lander System, HLS)
    - A significant change from the current lunar exploration is the presence of crewed vehicles, in orbit and on lunar surface, championed by the international Lunar Gateway program.
- Other Lunar science orbiters,
- Other Lunar exploration orbiters,
- Other Lunar Ascent & Descent modules,
    - Including manned vehicles
- Lunar surface mobile and stationary vehicles
    - At least 16 missions have been planned to deploy a lander, a rover, or both
    - Many of them will exploit the potential of Lunar far side science
- Lunar relay orbiters,
    - A huge number of them is given by SmallSat/CubeSat missions

A brief description of the most relevant ones is reported here below.

- Gateway

The Lunar Orbiting Platform-Gateway (LOP-G), also simply named Lunar Gateway, is an in-development space station in lunar orbit intended to serve as a solar-powered communication hub, science laboratory, short-term habitation module, and storage for rovers and other robots. It is an international program, including participation of Canada (advanced external robotics), Japan (habitation components and logistics resupply), ESA (providing the International Habitat (I-Hab), and the European System Providing Refueling Infrastructure and Telecommunications (ESPRIT), both of which will dramatically enhance the capabilities of Gateway, contributing to sustainable operations while paving the way for a future human mission to Mars), Russia (airlock).

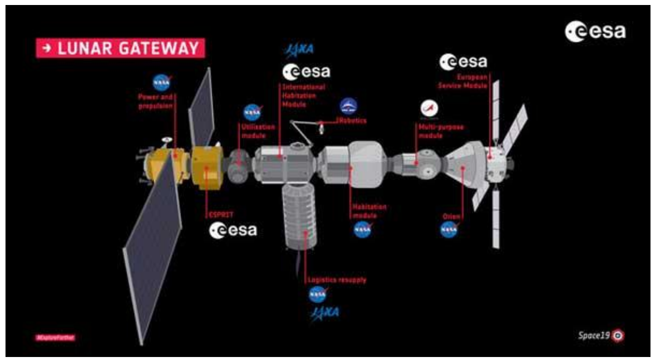

Figure 1: Lunar Gateway concept

The Gateway Communication System specification currently includes ([5]) S- and Ka- bands Radio Frequency (RF) communication interfaces which cover links with Earth, visiting vehicles, local users (EVAs) and Moon users, but OCRSG proposes also optical communications for all of these scenarios (also under study at NASA side with Lemnos).

- Artemis

Artemis is the name of NASA's program to return astronauts to the lunar surface.
The Artemis program foresees a sustained long-term presence on the lunar surface to use the Moon to validate deep space systems and operations before embarking on the much farther voyage to Mars. The Artemis program will also enable commercial opportunities on the lunar surface.
Artemis' final goal is to build the Artemis Base Camp at the South Pole of the Moon, depicted in Figure 2.

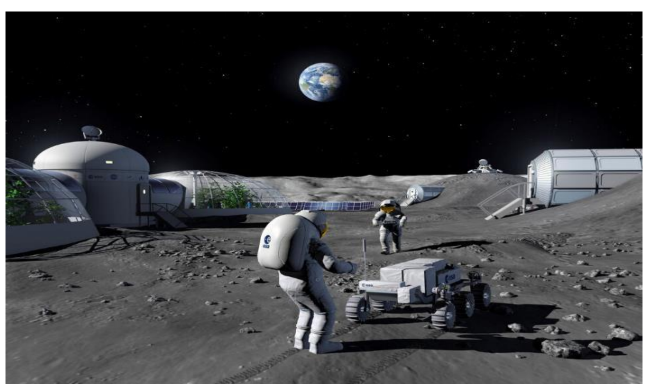

Figure 2: An artist's impression of what a lunar base could look like

In addition, NASA is also foreseeing a dedicated communication network around the Moon, named LunaNet.

- EL3

ESA is working on plans for a European Large Logistic Lander to provide different types of uncrewed missions, from supply runs for Artemis astronauts, to stand-alone robotic science and technology demonstration missions and even (still under discussion) a lunar return mission to bring samples to laboratories on Earth.

This European Large Logistic Lander (shortly EL3, [6]) is aimed at being an intermediate vehicle with size (8/9 tonnes) between the small landers being developed for science payloads (e.g. NASA CLPS, Roscosmos Luna-27, JAXA Smart Lander for Investigating the Moon- SLIM) and the large human lander employed for the Artemis program.
At this stage, EL3 relies on the Gateway for relay communications in S band and Ka band, having also a direct to Earth X-band capability.

- Moonlight

ESA's Moonlight initiative aims at providing commercial communications and navigation services to future lunar missions. The Initiative encompasses two steps:
    - Lunar pathfinder, also referred as "Commercial Lunar Mission Support services" will be developed by SSTL (UK) and once in orbit will offer data-relay services.
    - LCNS (Lunar Communication and Navigation System, [7]) will develop an infrastructure to provide communication and navigation services to future lunar missions. The services that LCNS shall provide will be: full lunar visibility, real time data relay with high throughput and continuous availability, one-way navigation, time transfer and time keeping.

- Commercial services (CommStar)

Currently, space communications have been primarily the responsibility of government owned, operated communications networks and managers. Commercial companies' participation as vendors of communications equipment, facilities, or as a network manager of hardware and software infrastructure, will accelerate Agencies' goals of commercialization.
CommStar Space Communications™ LLC, ("CommStar Space") seeks to lead that transition to commercial space communications and is planning a communication network to support the future lunar explorations. This network will be a "system of systems", providing an "end-to-end" data communications service between the Earth and the Moon. This objective requires access to a significant infrastructure, not only in space, but also across the Earth.
This design will start from the deployment of an advanced, proprietary data relay satellite ("CommStar-1"), under development to be located between the Earth and the Moon, which will not act purely as a data relay satellite, but it will also process the data in order to enhance the signal quality and provide robust and reliable communications. CommStar-1 relay infrastructure will be designed as a hybrid system for both radio frequency and optical (laser) communications.

The above-described lunar infrastructure will also necessarily foresee an Earth-based support, i.e.:
- Earth orbiting relays that provide service to lunar systems,
- Associated Earth Ground Stations and Mission Operations Centers.

they are not in the perimeter of OCRSG study, but mentioned because of paramount importance, also during the initial design phases, because their performance and availability directly impacts the sizing and design of the space segment.

2.2 Communications' scenarios and regulations

The foreseen lunar communications' infrastructure from [1] is shown here below in Figure 3.
This architecture is based on three networks:
- Earth Network
    - The Earth Network covers the so-called "Trunk link", i.e. the link with Earth.
- Lunar Relay Network
    - The Lunar Relay network includes the Proximity communications and the Cross Links (also called ISL – inter-satellite links).
- Lunar Surface Network
    - The Lunar Surface Network covers the surface outposts, including ground stations, fixed or mobile habitats, rovers, etc.

Such systems will involve a large set of terminals, located on different crafts or assets and with different needs and performances.
Concerning Moon orbiters and spacecrafts, we can see the Gateway and other orbiters as part of a relay satellite network (DTN, or other networks which can include also Cubesats in low orbit). Those nodes are inter-connected through ISL (inter-satellite links), and at the same time they will communicate also with the lunar surface (Proximity link).
On the lunar surface, on the other hand, there can be fixed (ground stations, both optical and RF, and the habitat modules) or mobile assets (rovers, astronauts in EVA but also portable communication stations), all interconnected. Of course, communication support will have to be tailored differently for the two types of users.

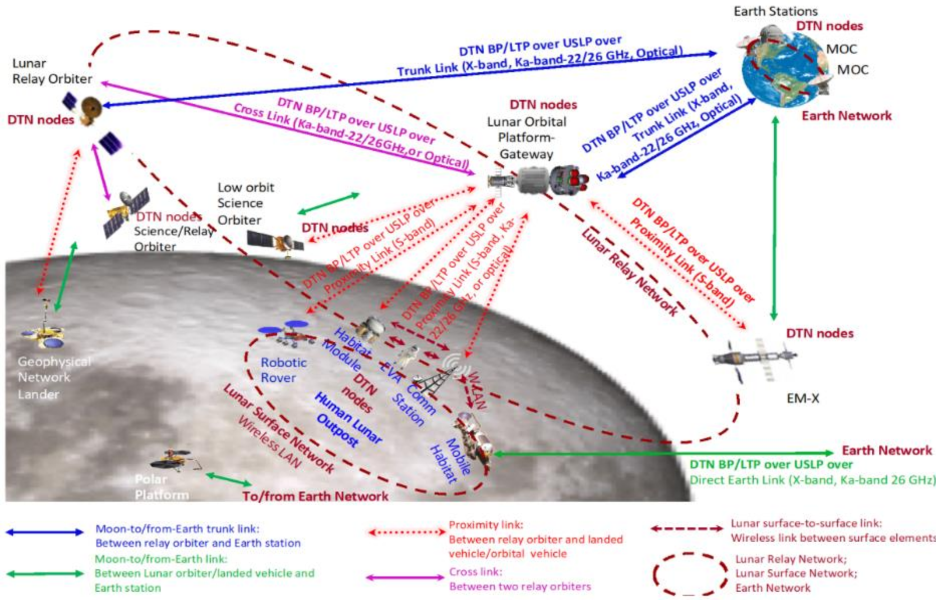

Figure 3: Lunar Communications architecture and Interfaces from [1]

The possibilities for each asset to communicate with the desired other asset directly or relaying through other nodes depends on the subsystem constraints, on the visibility and on the networks' management.
As an example, a Lunar habitat can communicate with Earth via a DTE (direct to Earth) link or via a Moon Station as a relay, and in space this link can be either direct or through a proximity link.
A relevant effort was put into the extensive analysis of the above wide set of use cases. Indeed, the optical terminal design is heavily impacted by constraints such as the needed signal power (linked to distance), Field of Regard and environment. Thus, a compromise between an all-tailored design (i.e. one terminal per use case), which would have allowed the best optimization but was not possible at this stage of the study due to the lack of input mission analyses, and an all-purpose design, which would have led to an inefficient over-design, has been proposed ending up with a limited set of terminals covering all needs with the maximum exploitation of state-of-the-art technologies (sec.4) as building blocks.
In particular, the studied type of links are:

- DTE: the link between the cis-lunar, lunar orbit and lunar surface to the Earth network. The link can be either direct (Moon-Earth surface) or also split into segments, for example Moon-Earth orbiter and then Earth orbiter (GEO)-Ground Station. [1] for DTE foresees X-, Ka- and optical communications. [2] also foresees S- and Q-bands.
  For DTE, OCRSG requires a minimum downlink rate of 2.1 Gbps, for a distance of 400000km. No requirements were given for the uplink, but the use case analysis proposed an initial value of 200 Mbps.
- Proximity: the link between a relay satellite and its relay service user. Relay service users can be lunar orbital spacecraft, descent/ascent vehicles, lander, rovers, and, potentially, astronauts equipped with portable communication device, communication stations/towers on surface, and human habitats.
  [1] and [2] for Proximity foresee UHF, S-, Ka- and optical communications.
  For Proximity, no data rate requirements were given, so we sized the link with the maximum DTE rate (2.1 Gbps) in downlink, assuming a Lunar fized station, and also a 200 Mbps symmetrical link, assuming a mobile/small surface asset, on a maximum distance of 70000 km (given by the Gateway orbit).
- ISL: the link between two relay spacecrafts. Of course, in this term a wide variety of vehicles is encompassed: Gateway, Other visiting vehicles, human landers, relay satellites, cubesats, etc. As those elements will be in different orbits, the reciprocal distances can vary a lot.
  [1] for ISL foresees Ka- and optical communications. [2] also foresees Ku- and Q-bands.
  For ISL, no data rate requirements were given, so we sized the link with the maximum DTE rate (2.1 Gbps symmetrical).
- Surface: the link between two landed assets.
  [1] for surface foresees IEEE 802.11 WiFi communications. [2] also foresees UHF and Ka-communications (recent studies are focusing on 4G/5G networks).

As none of the above recommendations foresee optical comms for the surface, this use case was not covered by the study optical terminals' design - also because the users' mobility does not allow the establishment of optical links because of the high involved dynamics.

From the scenarios gathered above, an outlook of a potential future optical communication system covering the needs of the future Lunar exploration activities can be drawn and is shown in Figure 4.

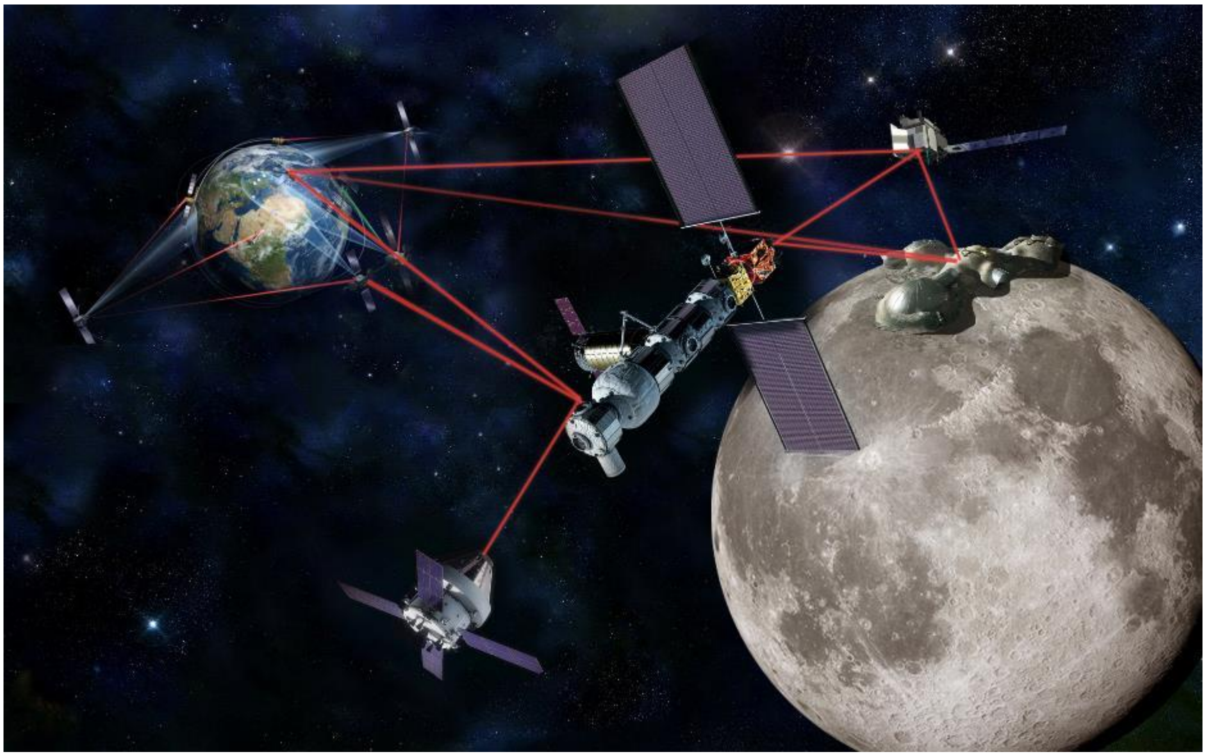

Figure 4: pictorial view of lunar, cis-lunar and Moon-to-Earth optical links.

3. STATE-OF-THE-ART SURVEY

3.1 RF vs optical comms

To meet the demands of high-definition video and data-intensive scientific research, the radio bands traditionally allocated for space research are showing their limits. For example, the Orion spacecraft will transmit mission-critical information to Earth via an S-band radio at 2 megabits per second. Barely 1 Mb/s will be allocated for streaming video from the mission. That's about one-fifth the speed needed to stream a high-definition movie on Earth.
To boost data rates even higher means moving beyond radio and developing optical communications systems that use lasers to beam data across space. Laser communications systems will allow transmission from the Moon of ultrahigh-definition 4K video back to Earth. Moreover, robust optical communications will allow future missions to receive software updates in minutes, not days. The scientific community will have access to an unprecedented flow of data between Earth and the moon.
In the next Table, a (not exhaustive) list of aspects showing the main differences between RF and optical links is presented.

Features	Rf technology	Optical technology
Bandwidth	Limited/regulated bandwidth	Very high bandwidth
Available data rates / volume	RF allow a medium throughput. Indicative maximum datarates: 50 Mbps in Ka-band (ref: KBT transponder for Gateway).	High throughput. Using an optical carrier whose frequency ranges from 1012 – 1016 Hz could permit up to 2000 THz data bandwidth.

Licensed	Limited and shared by multiple users.	Free.
Electromagnetic pollution	Major constrains depending on EM Regulations: Emissions regulated by ECSS	Minimal environmental risk (constrains related to eye-safety only).
Line of sight (LOS) and physical obstruction	Line of sight is not required and RF signals can penetrate certain obstacles (e.g. walls) depending on wavelength.	Alignment is demanding due to a highly directional transmitter and receiver (but now the technology allows it) while physical obstruction affect LOS.
Pointing constraints	Needed accuracies in the order of 1 milliradian.	Needed accuracies in the order of 1 microradian.
Multipath	It causes distortion on the radio signal (low BER), being problematic at high data rate.	Multipath effects are limited due to high beam collimation.
Accommodation	High accommodation constraints (especially with high diameters antennas).	Medium accommodation constraints
Power consumption	To cover long distances, high RF power is demanded. 300W.	Typical power consumption of Optel terminals: 25W
FOV/FOR	Large footprints in the order of thousands of kilometres for a signal from the Moon to Earth (covering entire States).	Small Field of View (FoV) and Field of Regard (FoR).
Security	Possibility of intercepting communication. Data links have to be protected	Robust to interception of remote communications.
Electromagnetic Interferences	Sensitive to EMI	No EMI issues.
Connectivity	Point-to-Multipoint links, with the capabilities to serve multiple stations/users with a single beam	Only point-to-point links with high collimated beams
Sites location and environmental effects	Higher per-site availability. System performances can be affected by the chosen Ground Station locations and weather conditions (rain and fog fade) with the increase of the signal frequency (especially K-band). Site diversity implementation (to be traded –off with frequency re-use or regulation issues) is envisaged in these cases.	Lower per-site availability. System performances are strongly affected by the chosen Ground Station locations and weather conditions (clouds obstruction, scintillation, scattering, …). Site diversity implementation is mandatory.

Table 1: Key differences between RF and Optical links

3.2 RF survey and analyses

During OCRSG study, a technological survey and a link budget analysis have been carried out in order to give a complete overview of the achievable performances with «traditional» RF communications (compatible with the indications reported in the previous section) w.r.t. optical links. The main driver of this state-of-the-art survey was on RF solutions which can compete to provide links on the Moon at 2.1 Gbps or more.

The survey for the spacecraft subsystem has been conducted to find units which should:

- Support frequency bands requested by IOAG
  - An analysis has been done to select the most promising band. Higher frequency bands typically give access to wider bandwidths, therefore, for lunar applications objective of this study, the potential RF technology that can achieve the highest data rates for lunar communications would have to foresee high frequencies, such as Ka- or even Q- bands.

  - In particular, Ka band allows the higher datarates at a reasonable atmospheric impairment cost (and this impairment is under study and optimization thanks to the evolving 5G technology usage). Moreover, it is already widely used in commercial communications, so that high data rate transceiver are already in place (even if with some functional limitations, as we will detail in the next sections), and the authorities and rules reported the previous section allow Ka band for all the lunar scenarios of interest in this study.
  - So, the main focus has been put on Ka-band RF technologies.
- Provide sufficient RF output power/Gain to support the link budgets at 2.1 Gbps
- Ensure a long lifetime (Up to 20 years for the Gateway and 5 years for the scientific missions)
- Be capable to sustain Moon environment: thermal (the space terminal should withstand operative temperatures from -20°C to 60°C, the Moon terminal should withstand operative temperatures from -130°C to +120°C), radiation, dust.

Table 2 summarizes the main outcomes.

Unit	**Types of surveyed units**	**Selected type**	**Candidate providers**	**Unit considered in the link budgets**
Transceiver	Ka (GMSK + PN RNG), Ka (OQPSK), Q and WAP/4G/5G	Ka transceiver OQPSK, no ranging	Blue Canyon Technologies LLC (USA) SOFTWARE DEFINED RADIOS.	No compliant unit available so far. Ideal transceiver: uplink 200 Mbps, downlink 2.1 Gbps in OQPSK modulation. From the technology survey, it is assumed that the development of such unit will be feasible when requested to the providers.
			L3Harris (USA) T-748 HIGH DATA RATE TRANSMITTER	
			Space Micro (USA) NANOCOM µKaTx-300 Ka-Band Transmitter	
			Tethers Unlimited (USA) SWIFT-X KTRX	
			Thales Alenia Space (France, Italy) KBT for Esprit	
RF amplifier	SSPA, LNA (low noise amplifiers), TWTA	TWTA in Ka-band	Thales Alenia Space Belgium TWTA	Maximum RF output power according to the frequency bands: 72W for DTE, 65 W for ISL, 40 W for Proximity
HGA	Ka-band classic reflectors or stowable antennas	Ka-band stowable antenna	Tendeg Space Antennas And Deployables (USA)	Tendeg Deployable High Gain Antenna gain =49.2 dBi + Automatic Pointing Mechanism (APM)
			Oxford Space Systems (UK) patented WRAPPED RIB ANTENNAS	

Table 2: RF state-of-the-art survey for the spacecraft subsystem

Some considerations have been also collected concerning the Ground Stations: even if they are not in the scope of this study, they have to be properly addressed as input for the link budgets.
The Ground Stations we are looking for must:

- Provide, or foresee to provide, Ka- bidirectional links on the “lunar” frequencies: 22.55-23.15 GHz uplink, 25.5-27.0 GHz downlink
- Support OQPSK modulation

Furthermore, a nice-to-have aspect for Ka-Ground Stations would be a favorable location from the climatic point of view. Dry conditions would be preferable in order to be able count on few moisture/rain/fog/snow effects.

ESA ESTRACK network provides three Ground Stations which are “nearly” compliant to the study needs. Cebreros and for Malargue GS in particular implement OQPSK modulation.

Concerning frequencies, there is no complete compliance instead. Indeed, the Ka-band is covered by Cebreros-1, Malargue-1, New Norcia and Redu-2, but with different frequencies with respect to the ones assigned to the Moon missions (22.55-23.15 GHz uplink, 25.5-27.0 GHz downlink).
According to ESOC (informally) , the Moon Ka frequencies are in program to be implemented in the ESTRACK network. An extrapolation from the above data leads to the following indicative performances for the future developments for a 15 m antenna: G/T of 46-48 dB/K, EIRP in the range 86-92 dBW assuming a 50 W – 200 W amplifier. These input has been considered as baseline in the link budgets.

The NASA DSN (Block V) receiver does not currently include GMSK, however it is able to cross-support GMSK modulation by use of the O-QPSK receiver implementation, at expenses of additional 0.7 dB to 1.0 dB demodulation mismatch losses. Concerning frequencies, there is again no complete compliance instead. Indeed, the Ka-band is covered, but, for the uplink, with different frequencies with respect to the ones assigned to the Moon missions (22.55-23.15 GHz uplink, 25.5-27.0 GHz downlink). The Ka-band receive capability in this band exists at Goldstone (DSS -24 and -26), Canberra (DSS-34, -36), and Madrid (DSS-54 and -56). Goldstone DSS-25 has also Ka-band uplink (but on the "wrong" frequency) at 300 W and, together with Canberra (DSS-35) and Madrid (DSS-55) it will receive 800 W Ka-band uplink before the end of 2024.

Besides ESTRACK and DSS networks, also the following companies, potentially compliant with the above requirements, have been found: Goonhilly (UK, Australia) and Astro Digital (USA). But again, frequency compliance is still not ensured.

Here below, the results of the link budgets based on the above input are summarized. They show that the requested performance is at the edge of current possibilities, again evidencing the advantage of optical communications in this scenario.

The requested data rate of 2.1 Gbps is:

- Marginally achieved for DTE downlink at 99% weather availability
    - HGA on board/Moon side, TWTA output power: 72 W
    - Distance: 400000 km
    - Worst case atmospheric effects (Atmospheric attenuation = 12.45 dB)
    - Ground Station characteristics from ESOC: G/T of 48 dB/K, EIRP of 92 dBW
    - Margin can be achieved with higher TWTA power (95 W), and/or Ground Stations with not worst-case atmospheric attenuation.
- Marginally achieved for ISL and Proximity link:
    - HGA on all assets, TWTA output power: 65 W
    - Distance: 70000 km
        - For Proximity, 70000 km is a limit worst case which is related to the maximum Gateway distance from the Moon,
        - However, imagining a dedicated network of lunar relay orbiters, they can ensure global coverage with a maximum distance of 8600 km; in this case the data rate is widely guaranteed.
    - Margin can be achieved with higher TWTA power (68W), and/or lower Ka frequency
- Not achievable for ISL with spacecraft mounting MGA on both sides
    - Distance: 70000 km
    - Maximum achievable data rates is 4.1 kbps
- Not achievable for Proximity links from spacecraft mounting HGA with rovers mounting MGA or LGA
    - Distance: 70000 km
    - Maximum satellite TWTA output power: 40 W
    - Maximum rover output power: 10 W
    - Data rates going from 2.8 kbps (LGA) to 1.6 Mbps (MGA)
    - Again, with lower distances (see above) e.g. at 8600 km, the following rates are guaranteed:
        - MGA: Forward 110 Mbps, Return 24 Mbps
        - LGA: Forward 850 kbps, Return 180 kbps
- Surface links between fixed terminals will sustain the requested 2.1 Gbps rate, as, assuming equal communication equipment, the maximum distance is much lower than the above cases due to the Moon surface curvature.

3.3 Optical survey and analyses

Figure 5 illustrates the simplified block diagram of a FSO (Free Space Optical) communication system for space applications. The modulated optical signal is collimated and transmitted by means of a telescope and, after the propagation through the atmosphere or the vacuum in space, it will be collected by another telescope and focused in to a small spot in a focal plane or directly coupled into an optical fiber, where a photodetector will transform it into an electrical one, which will be decoded to extract the original information.

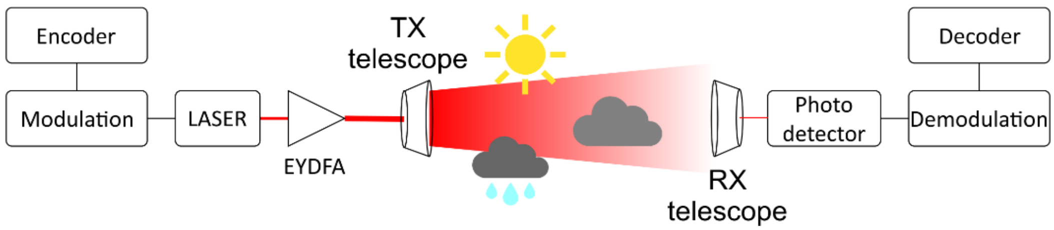

Figure 5: Simplified block diagram of the FSO communication system, with a propagation through turbulent channel

The modulated optical signal is collimated and transmitted by means of a telescope and, after the propagation through the atmosphere or the vacuum in space, it will be collected by another telescope and focused in a small spot in a focal plane or directly coupled into an optical fiber, where a photodetector will transform it into an electrical one, which will be decoded to extract the original information.

The main components at the transmitter side are:

- Laser transmitters. Coherent lasers for FSO are either high power solid state, or a classic commercial III/V semiconductor InGasAsP laser diode.
- Booster amplifiers. Erbium-doped fibers (EDFA) (or Erbium-Ytterbium-doped fibers, EYDFA)
- Telescope. Depending on the size of the aperture, a corresponding gain can be achieved. So, the gain is maximized by increasing the telescope's aperture, however, the telescope diameter could be limited by the overall size of the telescope due to limited space (as an example in spacecraft or satellite).
- Modulator: the modulation format affects the resulting BER (requested to be lower than 10^{-9}). In turn, this choice heavily drives the complexity of both the TX and RX terminals. Three modulation schemes have been addressed in this study:
    - On-Off Keying (OOK)
        - The simplest modulation format is intensity modulation, usually of non-return-to zero (NRZ).
        - We will consider NRZ-OOK to be optically amplified.
    - Differential Phase Shift Keying (DPSK)
        - DPSK encodes the digital information into a phase shift between subsequent bits (π-shift for 1 and 0-shift for 0).
        - Optical DPSK is usually obtained by external modulation of a CW lightwave, using a Mach-Zehnder modulator.
        - We will consider DPSK to be optically amplified.
    - Pulse Position Modulation (PPM)
        - In PPM (regulated by CCSDS HPE standard), information is transmitted by symbols. A modulation symbol consists of M time slots, each of duration Ts. Each symbols carries the information about a set of log2(M) bits, which is mapped to the position of a single pulse in one of the M slots.

The main components at the receiver side are:

- Detector ([8]): for optical communications in space, internal photoelectric devices are adopted as receivers. Some examples of such detectors: Semiconductor photodiode, avalanche photodiode (APDs), SPAD, phototransistor (BJT, FET), photoresistance, SNSPD, CCDs, vidicon.
    - NRZ-OOK and DPSK signals can also be detected by a pre-amplified receivers.

- o For photon starved applications like optical communications to the Moon, where the received power is expected to be very low, and where PPM modulation is preferred, Single Photon Avalanche Detectors (SPAD) and Superconducting Nanowire Single Photon Detectors (SNSPD) can be exploited..
- Demodulator:
  - o On-Off Keying (OOK)
    - the most efficient way to detect NRZ-OOK signal is by a pre-amplified RX.
    - Using OOK, 18 PPB are needed to get the target BER at 2.1 Gbps.
  - o Differential Phase Shift Keying (DPSK)
    - Optical DPSK can be detected with a Mach-Zehnder delay interferometer (MZDI)
    - Using DPSK, 9 PPB are needed to get the target BER at 2.1 Gbps.
  - o Pulse Position Modulation (PPM)
    - The key advantage of PPM is that it proves to be potentially very efficient in terms of optical detected energy, providing in principle the best photon efficiency, when the detector has a negligible thermal noise (as e.g. the superconducting nanowires).
    - Among the different PPM-orders, OCRSG selected PPM-16, which, for the case considered, could allow for a reasonable trade-off between complexity and performance.
    - Assuming a detector that is free from thermal noise, the expected sensitivity for 16-PPM at 2.1 Gbps is 3 PPB, but realistic experimental figures indicate a PPB=5.

Three main factors affecting the link budgets' result are derived from the propagation of the signal through the medium between the transmitter and the receiver:

- L_{FSO} indicates the propagation loss due to the diffraction effect,
- L_{atm} takes into account the atmospheric losses due to absorption and scattering (obviously, present only in case of DTE with OGS on the Earth surface)
- L_{turb} is the penalty introduced by the atmospheric turbulence ([9], obviously, present only in case of DTE with OGS on the Earth surface)

Still regarding the propagation of the optical signal, but besides the pure free space losses and atmospheric effects, other two factors are accounted for in the link budget:

- L_{vibr} are the losses due to pointing error,
- L_{fiber} is the loss due to the fiber coupling

All the factors introduced so far concur in the optical link budget analysis as:

$$P_{RX}=P_{Tx}G_{Tx}G_{Rx}L_{FSO}L_{atm}L_{turb}L_{point}L_{fiber}L_{Tx}L_{Rx}$$

- P_{RX} is the received optical power, P_{Tx} is the transmitted optical power
- G_{TX} is the gain of the transmitter telescope, G_{RX} is the gain of the receiver telescope (computed from the telescope diameter)
- L_{Tx} and L_{Rx} indicate the optical losses of optical telescopes at transmitter and receiver side, respectively (L_{Rx}+L_{Tx}= 4 dB, according to TAS-CH heritage).

Optical link budgets have been computed for the following scenarios:

	DTE (with Earth and GEO satellites)	**Proximity high rate**	**Proximity low rate**	**ISL**
Maximum distance	400000 km	70000 km	70000 km	70000 km
Data rates	2.1 Gbps downlink 200 Mbps uplink	2.1 Gbps downlink 200 Mbps uplink	200 Mbps downlink 200 Mbps uplink	2.1 Gbps two way

Table 3: optical link budget cases and input

and considering the following atmospheric conditions:

Atmospheric parameters	**Day-time values**	**Night-time values**
Wind speed at ground level [m/s]	23	8
Refractive index Structure parameter at ground level [$m^{-2/3}$]	10^{-13}	10^{-14}
Visibility [km]	15	15

Table 4: considered optical atmospheric parameters

The following scenarios have been analysed:

Parameter	**Simulated Values**			
Case	DTE Downlink	DTE uplink	Proximity Downlink and ISL	Proximity Uplink
Tx telescope diameter [cm]	5,13,20	40,100	13	5,13,20
Modulation format	OOK, DPSK, 16-PPM	OOK, DPSK, 16-PPM	OOK, DPSK, 16-PPM	OOK, DPSK, 16-PPM
Output Power [dBm]	43	43	33,43	30,43
Atmospheric effect	Day-time, night-time	Day-time, night-time	NA	NA
Rx telescope diameter [cm]	40,100	5,13,20	5,13,20	13,20
Adaptive optics	yes	no	no	no
Number of Rx apertures	1,4	1,4	1,4	1
Pre-amplifier noise figure [dB]	4	4	4	4
Elevation [°]	from 30° to 90°			
Link Margin [dB]	+3			
Target BER	uncorrected BER=10^{-3} and BER=10^{-9} applying the FEC scheme RS(255,239)			

Table 5: optical simulation cases for each scenario

For each scenario, the link budgets have been computed starting from the assumptions presented in the Table and analyzing the absorption, the scattering, the free space losses, the scintillation index, the arriving spot radius, the turbulence losses and the corrected Zernike modes as a function of the elevation angle.

An example for Daytime DTE downlink is shown here below (Figure 6), to present the adopted methodology. The computation shows the resulting PPB number for each elevation angle in different cases concerning the TX telescope diameter.
The agreement between the PPB results and the dashed thresholds for each modulation scheme gives as a result the feasibility of that combination of variables to close the link. From this feasibility, a baseline design for each case is derived. For example for this plot, a 5 cm transmitter telescope is not sufficient to achieve the minimum required PPB (equal to 5 considering a PPM modulation scheme). The 13 cm transmitter telescope is quite better for a PPM signal, but for a DPSK signal we can’t close the link for elevation angle below 40° with the 3 dB margin considered. The OOK is not an option for this small transmitter aperture. Among the considered ones and in daytime condition, the 20 cm diameter transmitter telescope is the only possible choice to establish a communication link at 2 Gbps from the Moon to the Earth using a 40 cm diameter single aperture receiver telescope. In this case the best modulation scheme is the PPM, so that we can ensure a link margin to increase the robustness and the reliability for each elevation angle.

The optical links budgets’ results for all the combinations shown in Table 5 are reported in Table 6.
It is worth noting some key facts:

- all links suffer from **high losses** (on the order of 100 dB), which are mostly due to diffraction effects and optical gain of the TX/RX telescopes; whilst beam spreading, i.e. diffraction, is due to Maxwell equations, telescopes are limited in size by practical issues (development of lenses/mirrors of large size, occupancy, ease of precise alignment);
- most of the links require high power (43 dBm) EYDFAs, whose application in terrestrial links is not considered and in space links is not consolidated; the long-term reliability of EYDFA may deserve a particular investigation;
- in our estimations we added 3 dB margins: this may be optimistic, given that it is the margin value used for RF links, that are consolidated;
- given that all links that are closed have **residual margin of few dBs**, any additional loss source may make the link unstable or not working; as example, this may be due to the widely varying atmospheric conditions (e.g. higher turbulence, light fog, thin clouds, pollution etc.);
- accurate alignment and tracking is also a key;

- further improvements in detection techniques, and FEC may make the links more robust at the cost of higher complexity.

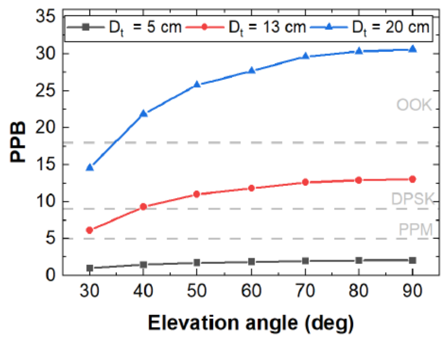

Figure 6: Daytime DTE downlink with D_{RX}=40 cm. Arriving PPB vs the elevation angle for single aperture transmitter telescope, having dimension D_{TX}=[5;13;20]cm. The minimum PPB required for OOK, DPSK, PPM modulation schemes are also reported.

	Tx diameter (cm)	Rx diameter (cm)	Tx Power (dBm)	Modulation format	Elevation Angle range (30- 90°)
DTE downlink	5	40	43	none	
	13	40	43	PPM	Y
	20	40	43	PPM, DPSK	Y
	20	40	43	OOK, PPM, DPSK	**only 40-90**
	13,20	100	43	OOK, PPM, DPSK	Y
DTE uplink	40	5	43	PPM, DPSK	**only 40-90**
	40	13	43	PPM, DPSK	Y
	40	20	43	PPM, DPSK	Y
	100	13,20	43	PPM, DPSK	Y
Moon-GEO downlink	5	40	43	none	
	13	40	43	PPM, DPSK	Y
	20	40	43	OOK, PPM, DPSK	Y
	13	100	43	OOK, PPM, DPSK	Y
Moon-GEO uplink	40	5	43	OOK, PPM, DPSK	Y
	40	13	43	OOK, PPM, DPSK	Y
	40	20	43	OOK, PPM, DPSK	Y
	100	13	43	OOK, PPM, DPSK	Y
Proximity downlink	13	5	33	none	
	13	5	43	none	
	13	13	33	PPM	
	13	20	33	PPM, DPSK	Y
	13	13	43	OOK, PPM, DPSK	Y
Proximity uplink	5	13	30	none	
	5	13	43	OOK, PPM, DPSK	Y
	13	13	30	OOK, PPM, DPSK	Y
	20	13	30	OOK, PPM, DPSK	Y
	13	20	30	OOK, PPM, DPSK	Y

Proximity uplink at 200 Mb/s	Minimum required power at Tx (dBm)
PPM	31
DPSK	33
OOK	36

Proximity downlink at 200 Mb/s	Minimum required power at Tx (dBm)
PPM	30.7
DPSK	32.7
OOK	35.7

Table 6: synthetic summary of the optical link budget results. In red we show the links that cannot be closed under present assumptions. In orange we indicate those that are partially achievable (e.g. under limited range of elevation angle) or that could be attained only by high-speed PPM (not yet available). The other cells have a light-green background, to indicate that these configurations are achievable under the assumptions we made in this document. In the bottom Tables, the sizing of the low rate proximity is also reported.

According to the above results, the following sizing is baselined (see Table 7, Table 8, Table 9).

	DTE Earth terminal		**DTE Moon terminal (either on Moon surface or in Moon orbit)**	
Terminal ID	**OGS**	**GEO OT**	**for link with the OGS**	**for link with the GEO OT**
Transmitted data rate	200 Mbps	200 Mbps	2.1 Gbps	2.1 Gbps
Telescope diameter	40 cm	40 cm	20 cm	13 cm
Transmitted optical power	43 dBm	43 dBm	43 dBm	43 dBm
Transmitted modulation	DPSK	OOK	16-PPM	DPSK

Table 7: DTE terminals baseline design. Column "DTE Earth terminal" is related to the terminals based on Earth (not under OCRSG design, but recalled here for reference on the considered assumptions) i.e. either the Optical Ground Station (OGS) or the GEO Optical Terminal (OT); column "DTE Moon terminal (either on Moon surface or in Moon orbit)" is instead related to the space terminals (objective of OCRSG design).

	Orbiter	**Moon Surface**
Terminal ID	**Orbiter terminal (Gateway or Satellite)**	**Lander terminal or Moon OGS**
Transmitted data rate	2.1 Gbps (forward)	200 Mbps (return)
Telescope diameter	13 cm	13 cm
Transmitted optical power	43 dBm	33 dBm
Transmitted modulation	OOK	OOK

Table 8: High rate Proximity terminals baseline design. Column "Orbiter" is related to the terminals in orbit around the Moon; column "Moon Surface" is instead related to the landed or surface terminals.

Terminal ID	**ISL terminal**
Transmitted and received data rate	2.1 Gbps
Telescope diameter	13 cm
Transmitted optical power	43 dBm
Transmitted modulation	OOK

Table 9: ISL terminals baseline design. Same design is assumed for all the terminals, even if on different orbits and space crafts.

A technical specification was derived from the above Tables; in the next section the derived design is reported.

4. USE CASES' ANALYSIS AND OT DESIGN

4.1 Use cases' analysis

Within each one of the mentioned type of links, several (11 in total) use cases have been studied, as far as the (limited) knowledge of the involved orbits and mission analysis allowed. The study is too extensive to be completely reported here, however some examples are shown here below in Figure 7 and Figure 8.
Indeed, the relative motion of the two terminals in an optical link determines the relevant FoR requirements, which directly drive the selection of a suitable pointing mechanism per use case. These requirements are added to the sizing constraints already shown in Table 7, Table 8, Table 9, which feed the optimization process that leads to the final definition of the OTs' design. After merging as many use cases requirements as possible, the minimum amount of different space terminals (6) is given, in order to meet all the use cases.
This is shown in Table 10. EGS terminals are not included in this list, since their design is not in the scope of this activity.

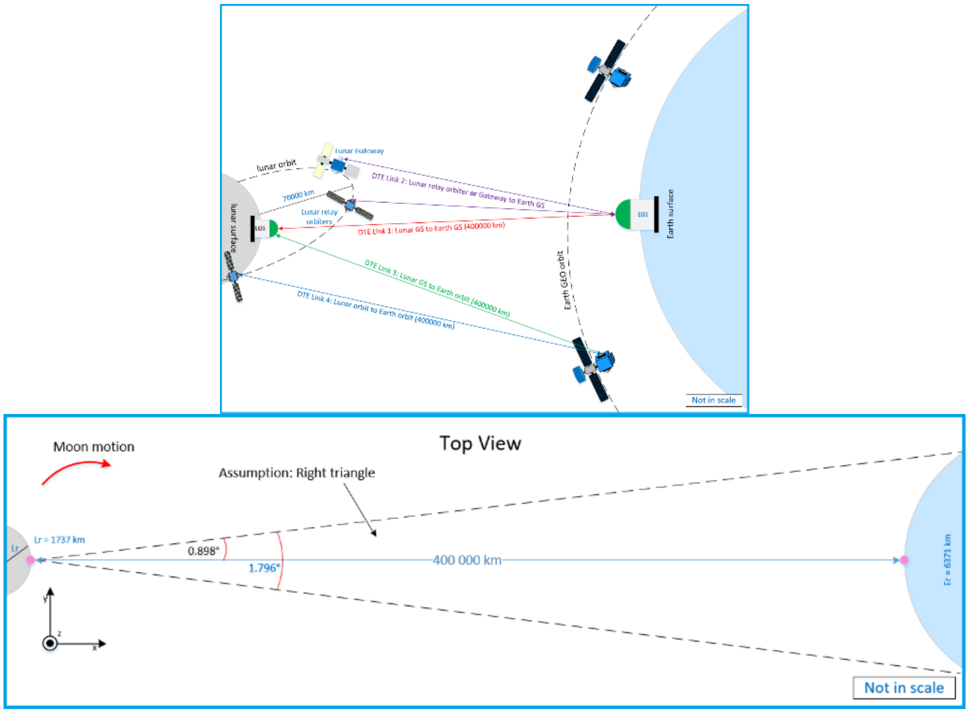

Figure 7: Direct to Earth links (DTE) and, below, an example of FoR study for DTE Link 1 - LCS OT, where it is shown that from the simple trigonometry applied, the LCS OT needs a very small FoR to cover the full Earth disk, due to the large distance between them. This amounts to approximately 2° in total (± 1°).

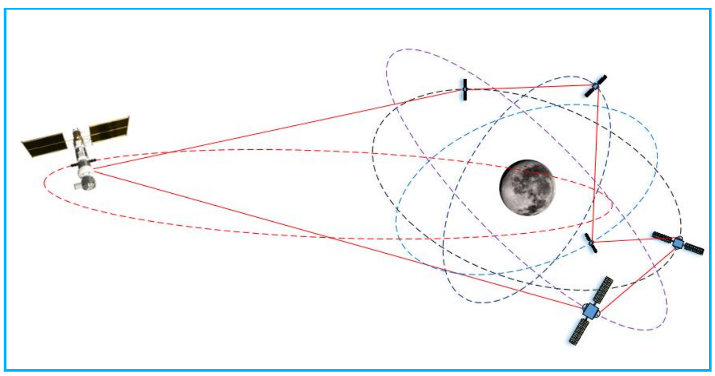

Figure 8: Capability 3 - Lunar Cross Links (OISL): Due to lack of knowledge of the lunar orbits exact placement, the safest approach dictates a fully hemispherical LORB OT for the ISL application.

Terminal	Diameter	Azimuth FoR	Elevation FoR	Optical Power	Assumed Modulation per link budget	Minimum Data Rate	Temperature	Use cases covered
LCS OT1	200 mm	± 10°	± 10°	43 dBm	16-PPM (DTE 1) & DPSK (DTG 1)	2 Gbps	Lunar surface	DTE 1 & DTG 1
LCS OT2	130 mm	± 180°	± 80°	43 dBm	OOK	200 Mbps	Lunar surface	Proximity 1
LORB OT1	200 mm	± 180°	± 80°	43 dBm	16-PPM	2 Gbps	Space	DTE 2
LORB OT2	130 mm	± 180°	± 80°	43 dBm	DPSK (DTG 2) OOK (Proximity 1, Cross link 1)	2 Gbps	Space	DTG 2, Proximity 1 & Cross Link 1
EGEO OT	400 mm	± 180°	± 20°	43 dbm	OOK	200 Mbps	Space	DTG 1 & DTG 2
LCS OT3	50 mm	± 180°	-50°/+90°	32.7 dbm	DPSK	200 Mbps	Lunar surface	Proximity 1

Table 10: OT variant list & main requirements

4.2 OT Variants Conceptual Design

In Figure 9, the detail on a single, generic optical terminal is shown.

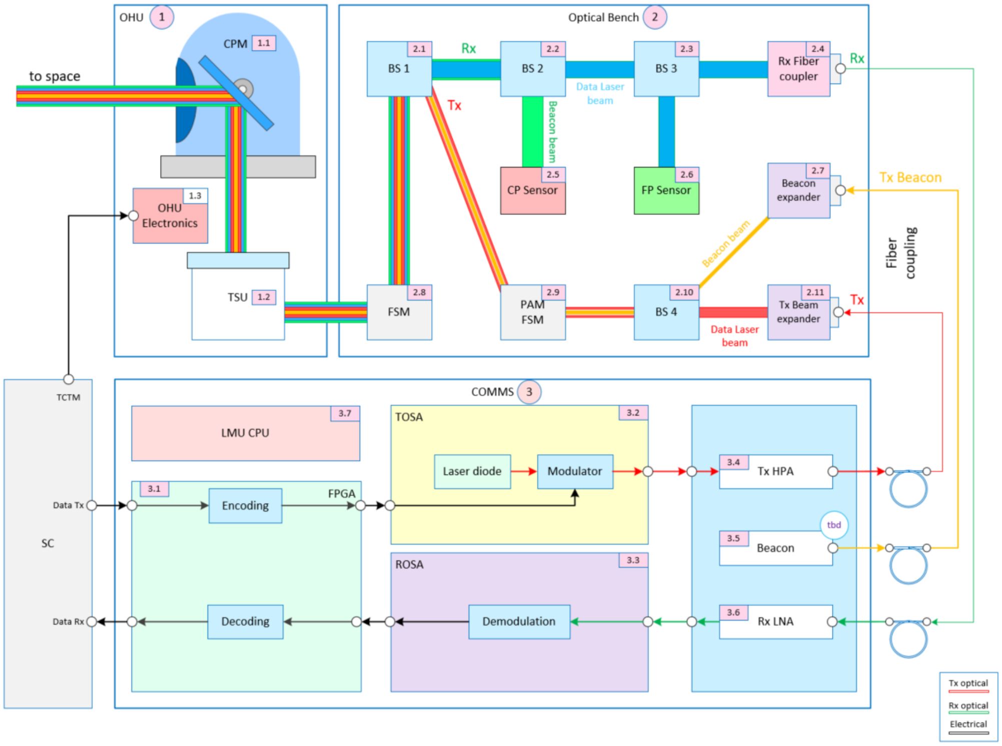

Figure 9: A generic Optical Terminal diagram

The 6 variants proposed in Table 10 follow the above architecture, mainly differentiating one from the other for what concerns the OHU (including the telescope and the CPM (Coarse Pointing Mechanism)) and LMU (Laser Modem Unit also covering power boosting, modulation and demodulation and coding).
The conceptual design was mainly focused on evidencing, for each variant, the estimated power consumption and mass, as well as any other relevant property from the preliminary conceptual design derived from the state-of-the-art market research (addressed in sec.5). The OHU power and mass estimations contain the following components: CPM, OH Structure, OH Electronics, Optical Bench, Telescope & MLI. The LMU power and mass estimations contain the following components: LMU structure, HPA, and the rest of the LMU electronics.

Terminal name	**LCS OT1**	**LCS OT2**	**LCS OT3**	**LORB OT1**	**LORB OT2**	**EGEO OT**
Terminal description	200mm terminal for Lunar Surface comms with Earth&GEO	Fully hemispherical FoR - 130mm double mirror periscope terminal for high rate Proximity comms from Lunar surface	50mm terminal for low rate Proximity comms from a rover	Fully hemispherical 200mm gimballed telescope - terminal for Lunar orbit to Earth surface comms.	Fully hemispherical FoR - 130mm double mirror periscope terminal for comms from Lunar orbiter with GEO, orbiters and Proximity	400mm terminal for GEO satellites
OHU total mass [kg]	38.6	37.9	< 7.5	70.7	44.7	122.1
LMU total mass [kg]	6.9	6.9	6	6.9	6.9	6.9
OT Total mass [kg]	**46.1**	**45.5**	**< 13.5**	**78.4**	**52.4**	**129.3**
OHU Total power [W]	36.0	25.0	< 5	36.0	25.0	73.1
LMU Total power [W]	343.2	343.2	55	343.2	343.2	343.2
OT Total power [W]	**379.2**	**368.2**	**< 60**	**379.2**	**368.2**	**416.3**

Table 11: OT variants' mass and power budget.

A major factor for the LMU design is dissipation of the DCDC converter and HPA thermal losses. This aspect impacts directly the mass of the total LMU structure. A rough calculation shows that in order to successfully dissipate 315 W of thermal losses, additional HW with a mass of 9.5 kg is needed, together with a radiative area of 1.3 m2 at platform level. The current OT conceptual design is not taking into account redundancy in any of the subsystems. Combination with the high reliability requirements (99.9%), yields to an additional total mass of 5.1 kg (again for the LMU).

5. TECHNOLOGICAL ROADMAP

Regarding the OHU, the proposed design for LCS OT2, LORB OT1, LORB OT2 is a fully hemispherical gimballed telescope. The mechanism selection is primarily based on the fact that such a CPM could cover the required FoR. The design is based on theodolite telescope applications, where the optical bench is placed directly below the gimbal. A conceptual diagram of the gimballed telescope is shown in Figure 10 below. This mechanism is currently at conceptual phase, especially for a 200mm terminal, which is complex to move and manage with the required pointing accuracy.

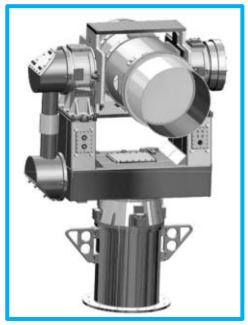

Figure 10: A fully hemispherical gimballed telescope

Concerning the other parts of the terminals, Table 12 identifies the differences between the component/subystem technology which has been assumed in the link budget analyses and baselined in the proposed design, and the state-of-the-art products, identifying the current gap between research and the market.

The main identified gaps concern:

- **Development and Space qualification of high-performance components.**
  Some of the technology needed for the designed systems has to be developed (i.e., high speed electronic decoders/encoders, high speed single-photo detectors…) or refined. In the last case, the already commercially available technology is not always fully space qualified, particularly with respect to mechanical stresses (acceleration, vibrations) and thermal variations.
  A key example are optical amplifiers or PPM modulation devices. At the target data rate, if we consider applying high order of PPM (>4) the bottleneck is mainly due to the electronics (i.e., encoder/decoders). At the moment, these types of detectors are commercially available only for low data rates (<1.2 Gb/s) and nevertheless not space qualified.
  Observing the present devices, in order to reach the 2.1 Gb/s goal data rate, communication with the DPSK format seems to be best compromise between performance and development efforts. The required technology is mostly available and should become dully space-graded qualified in a few years (some DPSK modulators/demodulators have been already tested for space applications). On the contrary, in order to use PPM technology, significant effort & resources are needed.
  FEC chipsets are available, although some tuning may be needed to adapt the final bit rate (FEC has been developed for terrestrial standards).
- **Adaptive optics needed at the Ground Station.**
  Special attention must be paid to the random fading that can be observed in a signal passing through a turbulent atmosphere: this has relevant technological impacts, which have found presently very limited countermeasures. First, it requires the development of suitable adaptive optics, which should mitigate the effect, both as post and pre-compensation combined with fiber-coupled transceivers. Mostly, even using AO, the possibility of fading has an impact on the performance of the receiver (e.g. recovery times of the clock-and-data recovery circuit) as well

as on the FEC performance, Both of these effects would significantly contribute to final communication stability and throughput.

- **OHU technology gaps**

  During the study, many different optical terminals have been designed at conceptual level.

For the LCS OT 1 variant, the proposed OHU has a desired aperture diameter of 200 mm, The TRL of this OHU design is 2. Regarding the EGEO OT variant, the baselined design has a diameter of 400 mm. The TRL of this OHU design is also 2. Regarding the LORB OT 1 variant, the OHU is a 200 mm, fully hemispherical gimballed telescope (Figure 9). No heritage has been individuated in the European Market for such a system. Thus, this is considered a large technology gap. Regarding the LCS OT 2 and the LORB OT 2 variant, the proposed OHU is a version of an existing product in the market,. The primary issue in the lunar surface case, is the temperature range (see bullet below). Regarding the LCS OT 3 variant, having an aperture of 50 mm, heritage exists also from past ESA studies.

- **LMU technology gaps**

  In most of the use cases a 43 dBm booster has been assumed. Regarding the HPA subsystem of the LMU, suppliers have already 40 dBm solutions for space applications and 43 dBm solutions for terrestrial applications. Although further confirmation is needed by the market, it is expected that the 43 dBm HPA shall be available for space applications in the near future.

  A rough power estimation of the 43 dBm LMU yields approximately 343.2 Watts. Thus, a major factor for the LMU design is dissipation of the thermal losses (see next bullet).

- **Lunar environment**

  Regarding environment requirements, the current available designs and technology allow for an operational temperature range of -20°C to 60°C. However, for the Lunar surface terminals a range of -130°C to +120°C is required. This temperature range is rather extreme compared to the already existing commercial optical terminals space applications. This is identified as a technology gap which has to be thoroughly investigated in the next phase of detailed OT design.

  Operation at extremely low temperatures has an impact on the mechanism bearings due to increase in friction, thus impacting directly motor torque requirements and CPM performance. Additionally, at extremely high temperatures, bearing lubricant evaporation becomes a major concern as well, affecting the performance and lifetime of the mechanism. Furthermore, high temperatures affect sensors and the majority of electronics performance from a thermal noise point of view, impacting the control system and thus the mechanism operation. Moreover, components where materials with different expansion coefficients are placed together (metal & glass) must be thoroughly tested as well for the full temperature range.

  Due to all the above reasons, the temperature requirements are expected to be a major driver in designing an OT for lunar surface applications and have to be thoroughly examined in the next project phases. It is considered, that this cannot be resolved on component/module level, but a thermal control and management of the sub-system and system level is required to achieve the needed reliability.

  Also dust can create multiple issues in rotating mechanisms which include bearings, since dust accumulation can increase bearing friction and potentially damage the mechanism. In order to prevent contamination within the bearing system, a bearing labyrinth seal with a narrow gap can be used. The most prone CPM to dust issues appear to be any kind of Mechanism design), since the Elevation bearings of the mirror are directly accessible from the aperture and thus directly exposed to the environment.

  Other components which might be affected are the mirrors. Apart from surface coating, active electrodes can be used to remove magnetic lunar dust particles. Accumulation on top of the sun filter glass, which is found underneath the mirror, can be dealt by slightly tilting the glass.

  The dust issue becomes particularly interesting from a mission analysis point of view. Due to the absence of wind on the lunar surface, the primary source of dust are lander's thrusters. Having this in mind, a thorough investigation needs to take place regarding the occurrence of this issue. To minimize dust entering the system, a shield can be used for parking the mechanism, thus blocking the aperture. More exotic and expensive solution would be to enclose the OHU within a removable cover.

Unit	Link Budget availability assumptions (DEL 05)	Identified Technology Gap
Adaptive optics	• For DTE links assumed only on OGS side for both Uplink & Downlink • For Proximity link assumed only tip and tilt (FSM) • For ISL assumed only tip and tilt (FSM)	Adaptive optics on Ground: N/A to OCRSG Solution available for FSM
RX: optical amplifiers / LNA	EDFA LNA (it has to be coupled with the booster), NF=4	Solution available with higher NF (>= 5 dB)
TX: Booster amplifiers	Erbium-doped Fiber Amplifier (EDFA): 43 dBm needed for many use cases	Space graded HPA available in the market: 40 dBm max power
Electronic decoders/encoders	Not addressed in this study but included in the LMU pwoer budget	Not addressed in this study
Modulator (Tx)	OOK: Mach- Zehnder modulator	Solution available
	DPSK: Mach- Zehnder modulator	Solution available
	16-PPM: Mach-Zehnder modulator with wide BW (40 GHz)	Solution available
Demodulator (Rx)	OOK: High sensitivity photodiode with fiber pigtails	Solution available
	DPSK: Mach-Zehnder delay interferometer (MZDI) & balanced photodiodes	Solution available, to be space-qualified
	16-PPM: can theoretically meet the link budget requirements if the technology gap is bridged in the future. Need for a quantum-limited receiver.	PPM receiver only at the Ground Station: not included in OCRSG design perimeter. However: not available
Laser	Classic commercial III/V semiconductor InGasAsP laser diode	Solution available, space qualification for the controller/electronics to be upgraded for the Moon (TBC)
Optical detectors	OOK: APD or PIN	Solution available
	DPSK: Balanced APD	Solution available
	16-PPM: Superconducting Nanowire Single Photon Detectors (SNSPD).	PPM receiver only at the Ground Station: not included in OCESG design perimeter. However: not available for high data rates.
Optical filters (after pre-amplifier)	OOK: Optimal filter of FWHM = 8GHz	Solution available, BW to be tuned
	DPSK: Narrow filter FWHM = 8 GHz	Solution available, BW to be tuned
	16-PPM: Much wider filter with tolerance (tentatively 100 Ghz)	PPM receiver only at the Ground Station: not included in OCESG design perimeter. However: solution available, BW to be tuned.

Table 12: comparison between baseline design (second column) and existing heritage (last column) for each component of the optical terminal.

In principle, the missing technology is currently at component level. In case that these components become readily available for commercial use, the design of the Optical Terminals can take place assuming also the availability of resources. A rough estimate would be that this technology could be ready in the frame of 5-7 years from now. As it has been previously stressed during this study, a thorough mission analysis needs to take place at operational system level, in order to properly define the exact requirements that such a complicated system has to meet.

6. CONCLUSIONS

The study started with a wide research on: Moon exploration missions, related communications scenarios, existing RF and optical technologies to cover such links.
The aim was to demonstrate where optical communications might be advantageous with respect to current RF technologies, in accordance with the IOAG recommendations which foresee laser links for DTE, Proximity and ISL, always using HPE modulation schemes according to CCSDS.
From this survey, together with the Customer requirements presented in the SoW, a set of technical requirements for a set of optical terminals that can guarantee high rate optical communications in the Moon environment have been derived through dedicated link budget analyses.
Accordingly, a proposed design is derived for this set of optical terminals, following this “top to bottom” philosophy.
Given the wide perimeter of this study, mainly based on future missions still to be defined, the design has been based on several assumptions and trade-offs, which of course can be questioned or reviewed in the future under the light of possible

new requirements or more detailed scenarios' descriptions (a relevant example is the high variability of examined Moon orbits, with altitudes going from 100 to 70000 km, that lead to a very generic over-design, which would be greatly optimized for more specific mission analyses results for each single orbiter).
We proposed a set of optical terminals derived from terminals available in the market, highlighting the technological gaps between the proposed design and the heritage.
We also derived a recommendation concerning the most suitable modulation schemes for the studied scenarios, referring to the current IOAG recommendations which foresee usage of HPE schemes for all Moon scenarios. For data rates of 2 Gbps, it is encouraged to use conventional modulation formats, e.g. DPSK or RZ-DPSK, whose implementation would benefit from devices available for terrestrial fiber communication.
These can also support simple upgrades to higher rates (10 Gbps). It is noted that US is also actively considering this option.
On the other hand, there are no known devices suitable for PPM-M that can sustain the high required rates (also due to timing jitter for pulses shorter than 125 ps); with PPM a more realistically achievable data rate would be rather in the order of 500 Mbps. Low M (< 4) might be preferred because of that.
PPM-16 is still unfeasible: e.g. a 2 Gbit/s PPM-16 would need ~40 GHz bandwidth; although it might be proposed to develop new types of devices with higher bandwidths, there is no guarantee that such a development is going to be successful. In addition, even in the case of successful development of such devices, the benefits would be on the order of few dBs.
Finally, longer links (e.g. Earth to Mars) would naturally support lower rates. Thus, high order PPM can be considered and existing superconductive detectors may be used. Still, the benefit of PPM must be carefully quantified and traded against other promising technologies.
In next phases, a revisit on the requirements on the OGS side is strongly advised, in order to allow the maximum use of heritage technology, in an effort to minimize development risk. This will offer also a "bottom to top" approach coming from the product line readily available.

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